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Executive Summary

WEAR OF STAINLESS STEEL

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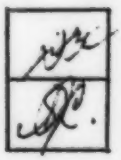
Due to the lack of applicable data on the wear performance of stainless steels over the range of test loads and speeds encountered in fuelling machines, a test program has been embarked upon to develop the appropriate data for use in fuelling machine design. The first stage of this work has been completed. As a basis for comparison of this series and future work, 17-4 PH pins sliding against a 17-4 PH disk have been tested over a range of loads and speeds similar to those found in fuelling machines using a pin on disk type test rig. In addition, Nitronic 60 pins sliding against 17-4 PH disks were tested over the same conditions of load and speed. Average weight loss results for all test conditions indicate that, on average, the Nitronic 60/17-4 PH combinations are a factor of 5.7 better than 17-4 PH/17-4 PH. However, under conditions of high load and speed, wear of the pin samples was similar although disk wear was always higher for the tests run with 17-4 PH pins.

An attempt has been made to fit the results to a computer model with some limited success but improvements could be made in the light of these test results with more appropriate selection of test conditions.



job	file	date	report no.
740624-577-051	824.45	November 20, 1985	85-308-K

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TO Mr. F.J. Kee
Director of Research

WEAR OF STAINLESS STEELS

P.E. Dale

To facilitate maintenance of the fuelling machines, the design of many sliding components is such that the FM housing is used as a bearing surface. This means that at least one of the sliding components is stainless steel, typically 17-4 PH to condition 1100 H. Wear evaluation tests have been performed at CRNL between 1964 and 1978 for over 100 different materials. The results of these tests are of limited application to most fuelling machine mechanisms, as the test used a journal bearing configuration. In addition, the information is very sparse as the tests were run over a wide range of loads and speeds. Other wear data on stainless steels are not readily available as stainless steels generally have poor wear performance and alternative materials are specified whenever possible. Exceptions are encountered when material properties such as corrosion resistance are specified before wear performance as is the case for many fuelling machine applications. In addition, published data which typically relates to conditions other than those encountered in in fuelling machines cannot be applied to FM systems as wear performance is not a material property but is strongly dependant on service conditions and environment. The present set of tests, therefore, were designed to develop specific data on the wear performance of stainless steel couples within a narrow band of conditions relating to fuelling machine operation.

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A list of several materials was determined which were of most interest for fuelling machine use through discussion with the client. Results for two of these materials, Nitronic 60 and 17-4 PH, are presented in this report. 17-4 PH is widely used in the fuelling machine and will therefore serve as a control for evaluation of Nitronic 60 and future candidate materials. Pins manufactured from these materials have been tested over a small range of loads and speeds sliding against 17-4 PH stainless steel disks in a pin-on-disk test machine. These two material combinations are expected to form the basis of an ongoing programme to evaluate a number of materials including self-lubricated sintered metal and ion implanted surfaces.

1.0 EQUIPMENT AND PROCEDURE

Wear testing of Nitronic 60 and 17-4 PH pins sliding on 17-4 PH disks was performed using the wear test machine described in Reference 1, with a pin-on-disk geometry, Figure 1, and conditions indicated in Table 1. Typical analysis for the materials under test is given in Table 2. All tests were run in a temperature controlled water bath and the direction of rotation was reversed at one minute intervals. Specimen conformity and surface finish were closely controlled by grinding the pin samples in the test fixture on new 600# grit paper prior to testing. Test duration was predetermined to be 60 minutes but this was overridden if wear displacement exceeded 1.27 mm, (0.05 inch). As this series of tests were the first to be run on the test machine, most test conditions were repeated to establish reproducibility.

Load and speed conditions, (Figure 2), were designed to enable a response surface to be computer generated over the selected range of loads from 2 to 18 kg and speeds from 2 to 10 cm/s. Data from the tests were collected by a desk top computer interfaced to the three transducers for displacement, friction force and specimen temperature on the wear test rig.

2.1 Displacement

An LVDT (linear variable differential transformer) transducer measures the combined displacement of the pins and disk and is not able to differentiate between pin and disk wear. However, this transducer gives a continuous output from which it is possible to identify running-in and equilibrium wear behaviour.

2.2 Torque

Original torque measuring equipment on the test rig was a single acting load cell which detected the friction force between the pin and disk by measuring the transmitted torque through the disk holder. This was modified during testing to a strain gauged beam measuring the same torque but able to do so for both rotating directions. This torque was converted to a coefficient of friction using the relationship:-

$$f = \frac{\text{friction force}}{\text{normal load}}$$

2.3 Specimen Temperature

A thermocouple was installed in all the disk samples 2.5 mm below the wear track. As all the tests were controlled to 90 C from a thermocouple in the water bath, the temperature measured by the sub-surface thermocouple did not vary outside the controlled range.

In addition to on-line computer monitoring, both pin and disk samples were weighed before and after testing and the wear debris collected and weighed after each test.

2.4 Computer Modeling

Data from weight loss measurements has been analysed in an attempt to fit a model which would predict pin, disk and total wear rates at loads and speeds between the test conditions. A calculated example indicating the actual and predicted values for combined pin and disk wear rates for 17-4 PH is included in Table 3. In this test programme all the wear rates were fitted to the same general formula:

$$Z = \exp^{b0} * L^{b1} * S^{b2}$$

Z = wear rate (mg/cm)
L = load (Kg)
S = speed (cm/s)

Values of b0, b1 and b2 for both Nitronic 60 and 17-4 PH are given in Table 4.

3.0 RESULTS

Table 5 contains a summary of results from the wear testing of the two material combinations. Values included in the Table represent averages of up to 4 tests at each condition. In addition to wear, average coeficients of friction for each test are included in this Table.

Equilibrium wear rates were calculated for each test from displacement-time plots. A typical example is shown in Figure 3 and demonstrates the two portions of a wear curve, namely running-in and equilibrium wear. Running-in occurs as the sliding surfaces are modified during the early stages of wear as a result of topographical and microstructural changes. Running-in usually has a high wear rate. As the strength of the subsurface increases and the contact surfaces are worn to distribute the contact stresses over a larger area, the wear rate decreases to a more stable situation which is known as equilibrium wear. Due to the operation of the displacement transducer, equilibrium wear rate refers to the combined wear of the pin and disk. Table 5 indicates equilibrium wear rates as a function of both time (mm/min) and sliding distance (mm/cm). Also included are weight loss measurements expressed as a function of sliding distance (mg/cm), for the pins and disk both individually and combined. Table 6 contains hardness readings for pin and disk samples before and after testing. One hardness reading is given for the surface of 17-4PH pins using a taper section tecnique.

Photographs of debris collected from tests run at conditions 3 and 9 for both material combinations are shown in Figure 4. Coarse debris in the form of severe abrasive wear particles was roughly sorted from the total debris for condition 9. The weight of coarse debris was 0.5846g for the Nitronic 60/17-4 PH and 0.4346g for the 17-4 PH/17-4 PH combination which represent 33.5% and 12.5% of the total debris collected respectively.

4.0 Discussion

4.1 Test Reproducibility

Reproducibility of test results for repeat test conditions was found to be excellent considering the variable nature of wear testing which has been reported to be as high as a factor of three on repeat tests. The maximum error was determined to be +/- 20% from the mean value for weight loss measurements.

4.2 Wear results

Results given in Table 5, indicate wear rate in a number of forms. The most common is the true equilibrium wear rate which is determined from the LVDT on the wear test rig. Equilibrium wear is the linear portion of the displacement-time plot occuring after running-in, Figure 3.

Using equilibrium wear rate as a basis for comparison, the anti-galling Nitronic 60/17-4 PH combination has a much lower wear rate over the range of conditions tested. Although care should be exercised when using average wear rates over a range of

conditions, an indication of the difference between the two materials is that the average wear rate for Nitronic 60/17-4 PH is a factor of 3.4 better than for the 17-4 PH combination. However, at low sliding speeds of 2cm/s when the equilibrium wear rate for the Nitronic 60 is almost zero there is a factor of upto 380 difference between the two material combinations. In addition, at the most severe conditions of load and speed the difference between the materials was only a factor of 1.6 to 1.8 in favour of the Nitronic 60. Although these figures are a good indication of the wear performance of the two materials, they cannot give the complete picture. The measurement will not differentiate between a test in which all the wear takes place on the pin and one in which all the wear occurs on the disk.

To separate the wear of the pins from the disks, weight loss measurements have also been used to calculate wear rates, Table 5. These wear rate values include the running-in portion of the wear which can vary from sample to sample depending on factors outside the test parameters. Running-in is necessary to produce optimum surface properties for minimum long term wear. A number of mechanisms can operate during running-in including dispersal of asperity contacts, surface work hardening and oxide generation. It can also depend on a number of test variables such as the degree of conformity between the pins and disk at the start of the test and contamination of the wear surfaces. All service components have to go through a running-in stage and the amount of material removed during the stage can influence the expected life. Typically, material lost during running-in represents a small fraction of total wear during the life of a component. However, in systems with very little sliding, components may never enter the equilibrium portion of the wear curve in which case running-in wear can be very significant. For some sliding components in the fuelling machine, therefore, it may be more relevant to use total weight loss measurements as an indication of wear performance than the more usual equilibrium wear rate.

Weight loss measurements have been converted to weight loss per unit sliding distance from the original unit time to take into account the increase in sliding distance as speed increases for the fixed-time test. The difference between the average pin and disk wear of Nitronic 60 and 17-4 PH, using weight loss per cm sliding as the basis for comparison, shows the Nitronic 60 to be a factor of 5.8 better than the 17-4 PH. This value is similar to the figure of 6.2 for eqilibrium wear per cm sliding calculated from LVDT measurements.

4.3 Wear mechanisms

A number of significant differences between the two materials become apparent when the results of weight loss measurements are examined. For example, disks from the Nitronic 60 tests run at 2 cm/s have a negative wear rate due to transfer of material from the pins. This is classical adhesive wear behaviour.

Figure 5 indicates the trends in wear performance for the materials over the range of test conditions. It is clear that as the speed is increased for a given load, the wear per unit sliding distance on both the pins and the disks increases for Nitronic 60 but decreases for 17-4 PH. In addition, as the load is increased for any given speed, the slopes of the wear curves for Nitronic 60 tend to increase whilst those for 17-4 PH decrease. From an examination of the pin and disk surfaces after testing the wear mechanism appears to be a combination of adhesion and abrasion. In adhesive wear, micro-welds are formed between the sliding surfaces which generally fracture to transfer material from one surface to the other. This transfered material is very highly stressed and is reflected in micro-hardness readings of upto 850 Hv at the surface of the 17-4 PH material compared to an original hardness of around 460 Hv, Table 6.

Because of the high hardness, these transfered particles can lead to severe abrasion of the counter-surface. The overall superior performance of the Nitronic 60 is due to its "anti-galling" properties. Nitronic 60 was developed by Armco Steel co. for use in adhesive wear environments and has been shown to perform well under such conditions, /2-3/. The reason for the improved performance of the Nitronic materials over other austenitic stainless steels is thought to be due to oxide film formation as a result of the high silicon content. This film not only contaminates the interface but also acts as a low shear strength lubricating film between the sliding surfaces which is further enhanced by the effect of manganese and nitrogen which serve to strengthen the substrate and support the film. Although Nitronic 60 has properties which enhance its adhesive wear resistance, it has a lower resistance to abrasive wear as a result of its lower hardness. The initial hardness of Nitronic 60 is 188 Hv compared to 17-4 PH which has a hardness of 466 Hv. It is the hardness at the end of the test which is most indicative of abrasive wear resistance as a considerable amount of work hardening occurs during wear. Although the Nitronic 60 has significantly increased in hardness, it still has inferior abrasive wear resistance to 17-4 PH at the end of the test. The results shown in Table 6 indicate a maximum surface hardness of 852 HV for 17-4 PH with a mean value of around 750 Hv. Although the surface is the optimum position to measure hardness at the end of the test, it requires the use of a taper section technique which was not repeated for Nitronic 60 pins.

Evidence from post test examination of wear surfaces and wear debris indicates that at low speeds and loads the main wear mechanism is adhesion but at more severe loads and speeds abrasion becomes more significant as work hardened transferred particles remove material by plastic deformation and cutting. Evidence of this can be seen from the amount of severe wear particles in the debris at high loads and speeds, Figure 4. That abrasion is more severe for the Nitronic 60/17-4 PH combination can be determined from the proportion of severe abrasive particles in the test debris. For the Nitronic 60/17-4 PH couple this amounted to aproximately 33% but for the 17-4 PH/17-4 PH combination, the proportion was only 12% of the total debris. The most significant consequence of this behaviour is that at high loads and speeds, the weight loss per unit sliding of the 17-4 PH pins is less than that of Nitronic 60. However, the combined wear of pins and disks is still greater for 17-4 PH due to the more severe adhesive wear component. It would appear that when one surface of a sliding couple can be sacrificed, a 17-4 PH material may be superior to Nitronic 60 at the higher test loads and speeds. Weighed against this will be the amount of wear debris put into the system using the 17-4 PH material combination.

4.4 Friction Results

The anti-galling properties of Nitronic 60 can also be seen from the significantly lower coefficient of friction when sliding against 17-4 PH, average 1.1, than 17-4 PH sliding against itself, average 1.7, Table 5. This level of friction indicates metal to metal contact between the pin and disk surfaces for both material combinations and illustrates the inability of water to provide adequate lubrication under fuelling machine conditions.

4.5 Computer Modeling

Although the test matrix was determined to allow generation of a response surface using SAS (Statistical Analysis System) utilities, it was found that the generated surface did not accurately model the actual wear data. The model predicted negative wear rates for both pins and disk at the extreme test conditions. Largely through empirical methods, the final form of the equation was determined which gives a reasonable fit to the data considering that the test matrix was not selected for this approach.

The fundamental law of adhesive wear as determined by Archard is given by :-

$$V = \frac{kLx}{3p}$$

V = Wear Volume, L = Load, k = Wear Coefficient
x = Sliding Distance, p = Penetration Hardness

Volume wear per unit time, therefore, is proprtional to load and sliding speed. However, there are relatively few cases where this law holds and for most examples the wear rate is proportional to some factor of load and speed. Since the wear in this case is a combination of both adhesion and abrasion, it is not surprising that the form of the equation is not the same as the fundamental form.

Table 3 also indicates the upper and lower 95% confidence intervals for the data in addition to the predicted value. A computer program is available to generate Tables for pin, disk and total wear at any confidence interval (CI) for both Nitronic 60 and 17-4 PH over the range of test conditions. The reason for the large range for the CI is the relatively small number of test points. If it is intended to continue with modeling for the next series of tests, the number of test nodes will be increased to enable more accurate fitting.

4.6 Further work

There are two materials outstanding from the initial list of candidate materials, namely Deva metal and Waukesha 88. In addition to testing these materials it is intended to investigate ion implantation which appears to have a large potential for improving the wear performance of stainless steel in localized areas such as encountered in the fuelling machine.

5.0 CONCLUSIONS

5.1 Over the range of loads and speeds tested Nitronic 60 sliding against 17-4 PH exhibits a lower wear rate than 17-4 PH sliding against itself. However, at the higher test load and speed conditions, the wear of the 17-4 PH pins was lower than the Nitronic 60 pins although the disk wear was higher for the 17-4 PH pin test.

5.2 The coefficients of friction between the Nitronic 60 and 17-4PH were less than from 17-4 PH sliding against itself but both coefficients indicated metal to metal contact between the sliding surfaces.

5.3 At the higher loads and speeds some of the wear debris was in the form of spiral chips similar to machining swarf which could cause some problems in the fuelling machine system. At low loads with the Nitronic 60 there was essentially no debris formed.

5.4 Computer modeling seems very promising but requires a test program to be developed to complement the analysis. The present series of tests was invaluable as an aid to designing such a program.

6.0 ACKNOWLEDGEMENTS

Tests were performed by Mr. A. George and Mr. C.R. McGowan of Mechanical Research and Dr A.H. Chan of Operations Research was responsible for development of the computer model including a large volume of work on contour plots and response surfaces which was not included in the report.

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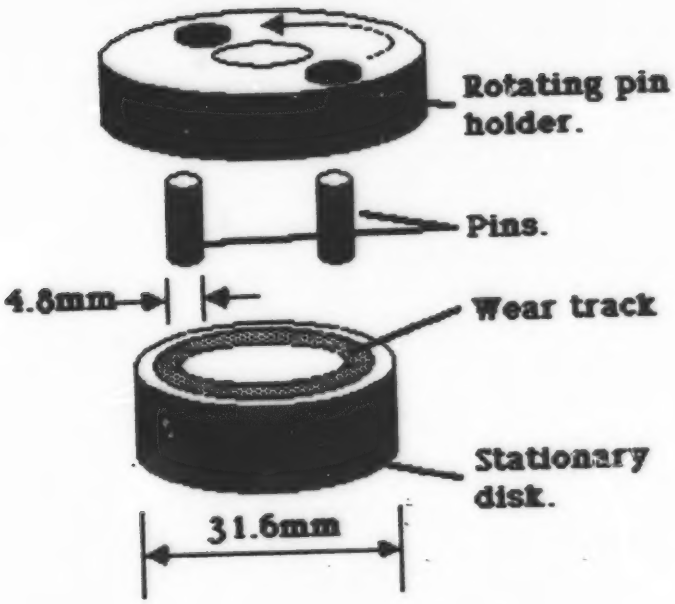


Pin and disk geometry.

FIGURE 1

PIN ON DISK GEOMETRY

TABLE 1

Test Geometry and Conditions

	METRIC (MM)	IMPERIAL (INCHES)
PIN DIAMETER	4.8	.189
AREA OF PIN CONTACT (two pins)	36.2	.056
DISK DIAMETER	31.6	1.244
I.D. OF WEAR TRACK	18.9	.744
O.D. OF WEAR TRACK	28.5	1.122
AREA OF DISK WEAR TRACK	357.4	.554
	CM/S	RPM
SPEED	2, 5 & 10	16, 40 & 80
	KG	LBS
LOAD	2 to 18	4.5 to 39.5
TEMPERATURE	90 C +- 5 C	

TABLE 2

Material Chemical Analysis

	C	Mn	Si	Cr	Ni	P	S	N
NITRONIC 60 UNS S21800	.10	7-9	3.5-4.5	16-18	8-9	.06	.03	.08-.18

	C	Mn	Si	Cr	Ni	P	S	Cu	Nb+Ta
17-4 PH UNS S17400	.07	1.0	1.0	15-17.5	3-5	.04	.03	3-5	.15-.45

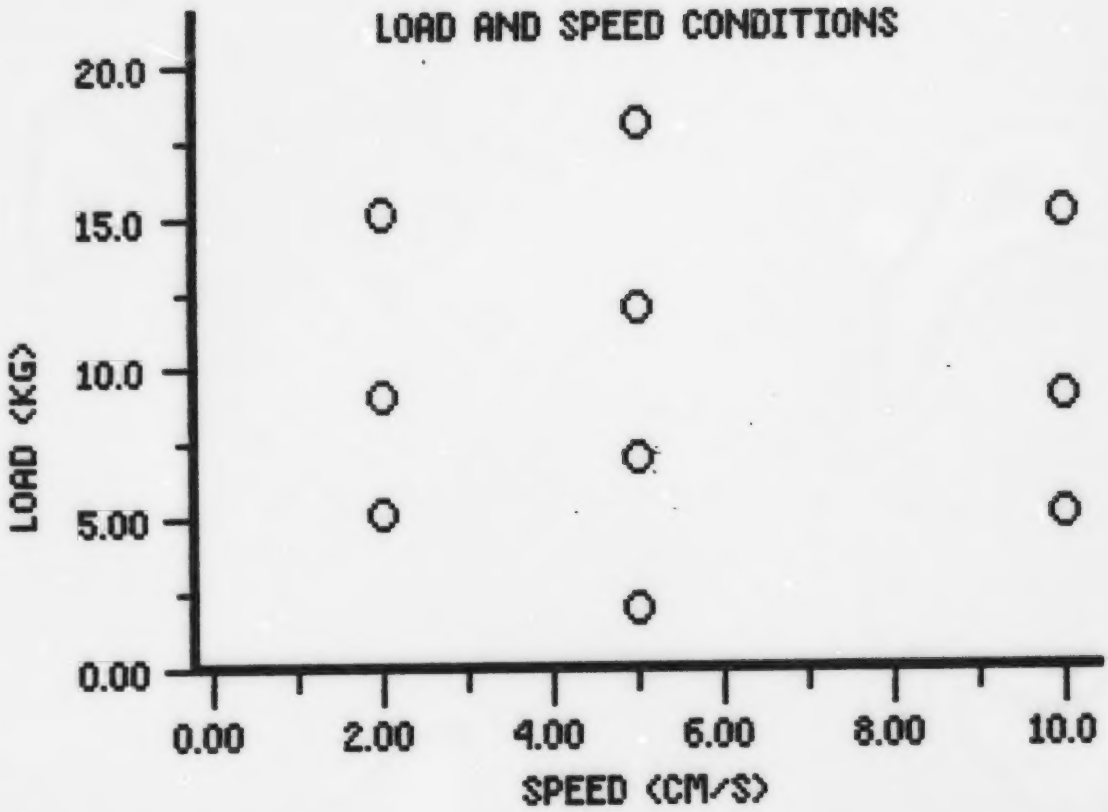


FIGURE 2

LOAD AND SPEED CONDITIONS

TABLE 3.

Computer predicted values, upper and lower confidence intervals for 17-4 PH pin, combined pin and disk wear.

LOAD (KG)	SPEED (CM/S)	MEASURED WEAR RATE (MG/CM)	PREDICTED WEAR RATE (MG/CM)	L95	U95
5	2	0.170	0.183514	0.121031	0.27825
9	2	0.430	0.364846	0.241414	0.55139
15	2	0.700	0.662941	0.433229	1.01445
2	5	0.037	0.040258	0.026263	0.06171
7	5	0.190	0.174152	0.118996	0.25487
12	5	0.320	0.327037	0.221743	0.48233
18	5	0.420	0.525371	0.350345	0.78784
5	10	0.110	0.083878	0.055753	0.12619
9	10	0.150	0.166760	0.111017	0.25049
15	10	0.310	0.303010	0.198893	0.46163

TABLE 4.

Values of b0, b1 and b2 for computer model.

PIN MATERIAL		b0	b1	b2
NITRONIC 60				
	PIN	-12.514634	1.908210	1.260874
	DISK	-13.028568	2.682405	1.961773
	COMBINED	-14.529496	2.432700	2.999935
17-4 PH				
	PIN	-3.266528	0.340319	-1.339437
	DISK	-3.498198	1.226872	-0.432569
	COMBINED	-3.239889	1.169109	-0.486455

TABLE 5

Summary of Test Results

CONDITION NITRONIC60	LOAD (KG)	SPEED (CM/S)	COEFF OF FRICTION	EQUILIB. WEAR RATE (MM/MIN)	EQUILIB. WEAR RATE (MM/CM SL)	TTL. WEAR RATE (G/CM SL)	TTL. PIN WEAR (G/CM SL)	TTL. DISK WEAR (G/CM SL)
1	2	5	1.0	0.00010	3.33E-07	2.22E-07	5.56E-08	1.67E-07
2	5	2	1.2	0.00010	8.33E-07	3.19E-07	3.19E-07	-6.39E-07
3	5	10	1.2	0.01050	1.75E-05	3.20E-05	2.17E-06	2.98E-05
4	7	5	1.0	0.00100	3.33E-06	9.78E-06	1.00E-06	8.78E-06
5	9	2	1.2	0.00010	8.33E-07	5.69E-07	5.69E-07	3.47E-07
6	9	10	1.2	0.02100	3.50E-05	7.66E-05	3.88E-06	7.27E-05
7	12	5	1.0	0.00500	1.67E-05	5.03E-05	4.11E-06	4.61E-05
8	15	2	1.2	0.00010	8.33E-07	6.94E-07	6.94E-07	-1.04E-06
9	15	10	1.2	0.02900	4.83E-05	1.61E-04	7.69E-06	1.54E-04
10	18	5	1.1	0.02450	8.17E-05	1.69E-04	1.12E-05	1.58E-04
(A) Average Value			1.1	0.00914	2.05E-05	5.00E-05	3.17E-06	4.68E-05
17-4 PH								
1	2	5	1.5	0.01025	3.42E-05	3.69E-05	5.16E-06	3.17E-05
2	5	2	1.7	0.01450	1.21E-04	1.71E-04	2.36E-05	1.47E-04
3	5	10	1.7	0.02900	4.83E-05	1.13E-04	3.42E-06	1.09E-04
4	7	5	1.7	0.02930	9.77E-05	2.05E-04	1.06E-05	1.95E-04
5	9	2	1.7	0.02850	2.38E-04	4.30E-04	3.52E-05	3.95E-04
6	9	10	1.8	0.03500	5.83E-05	1.51E-04	3.72E-06	1.47E-04
7	12	5	1.6	0.03550	1.18E-04	3.21E-04	9.99E-06	3.11E-04
8	15	2	1.7	0.03800	3.17E-04	7.04E-04	3.89E-05	6.66E-04
9	15	10	1.7	0.04700	7.83E-05	3.11E-04	4.13E-06	3.07E-04
10	18	5	1.6	0.04600	1.53E-04	4.17E-04	1.02E-05	4.07E-04
(B) Average Value			1.7	0.03131	1.26E-04	2.86E-04	1.45E-05	2.72E-04
(B)/(A) Ratio of 17-4 PH to Nitronic 60			1.5	3.4	6.2	5.7	4.6	5.8

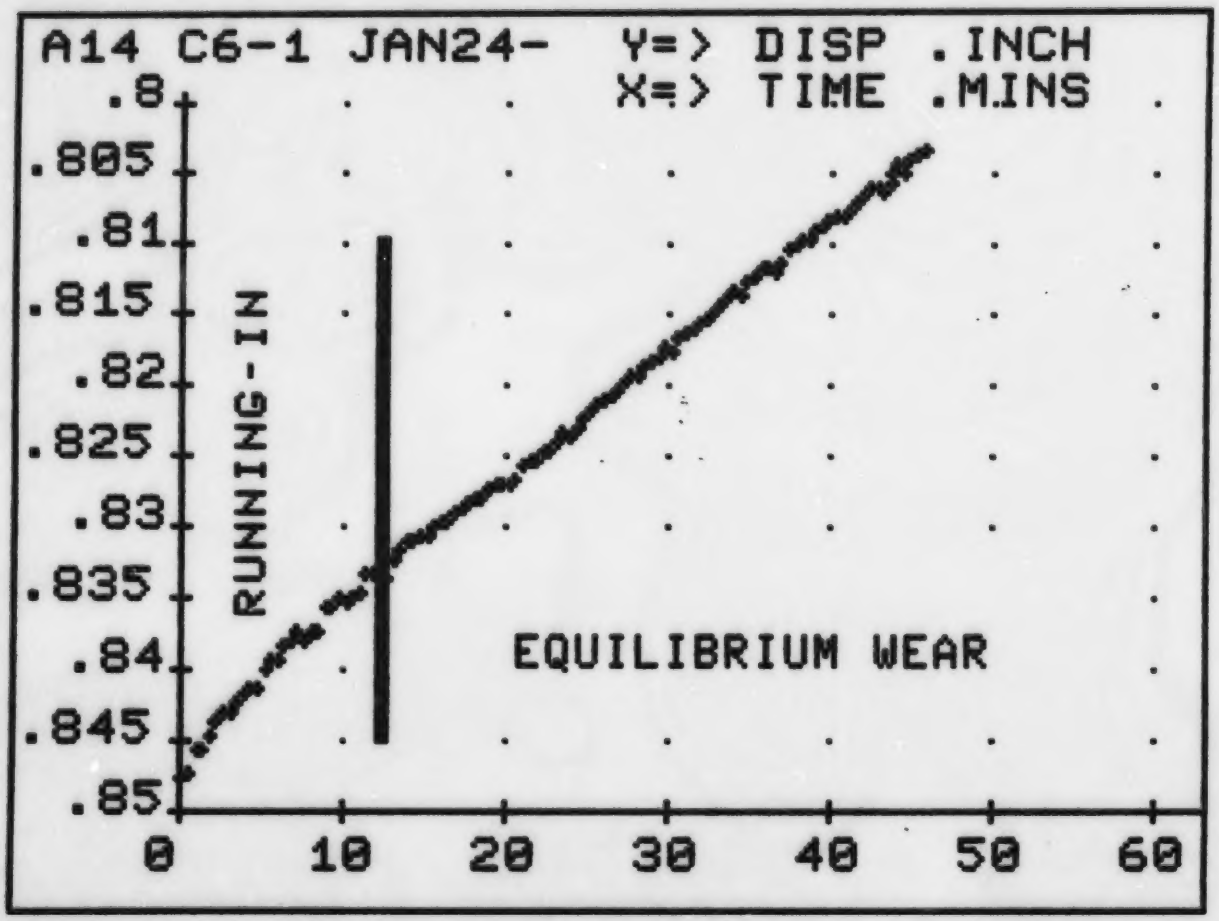


FIGURE 3

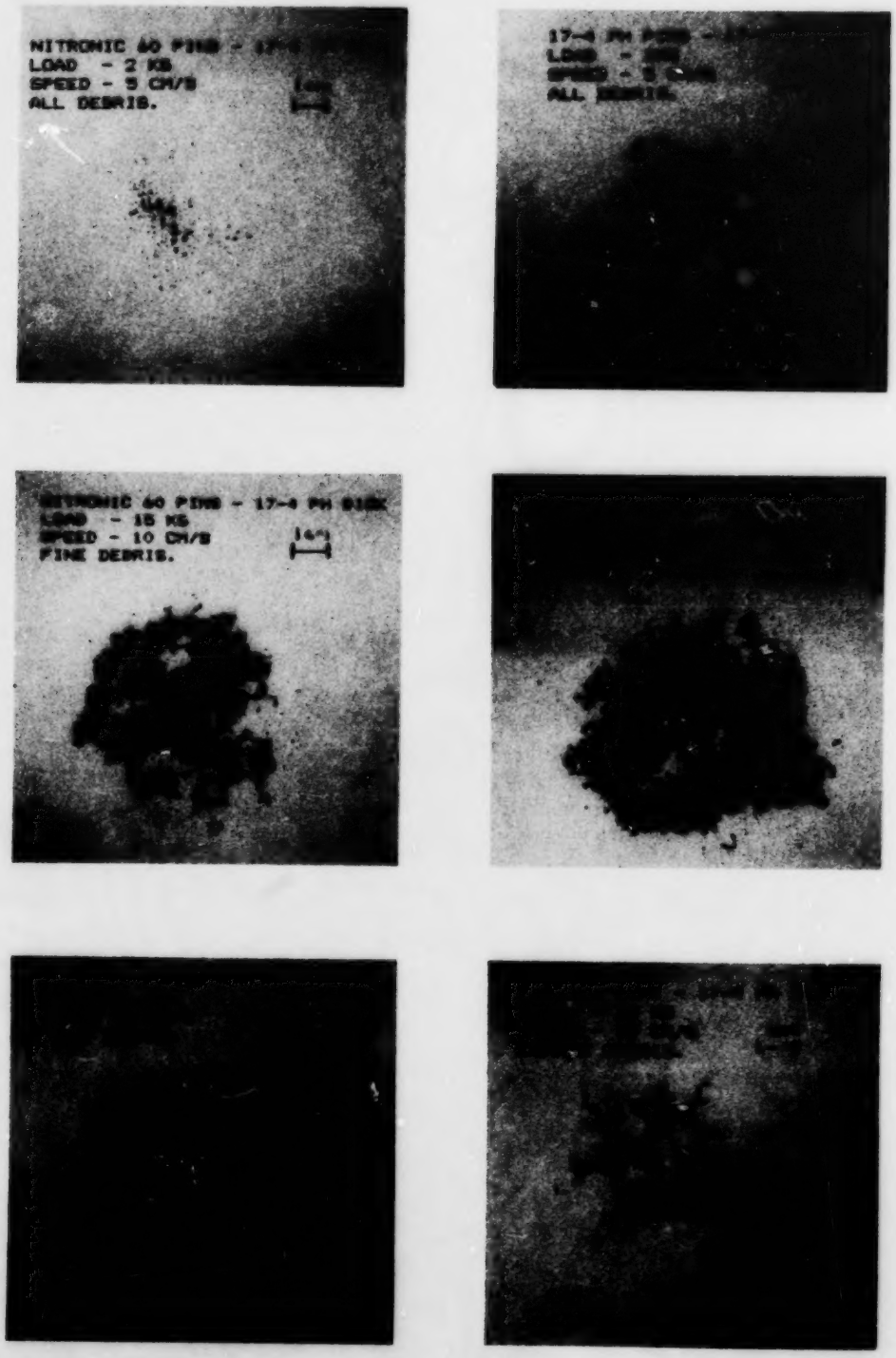
TYPICAL DISPLACEMENT-TIME PLOT

TABLE 6

Vickers hardness test results

	Before Test	After Test (close to surface)	(at surface)
	VPN	VPN	VPN
NITRONIC 60 PINS	188	338	
17-4 PH PINS	466	530	850
17-4 PH DISKS	350		

FIGURE 4. Macro Photographs of debris from tests run at conditions 3 and 9.



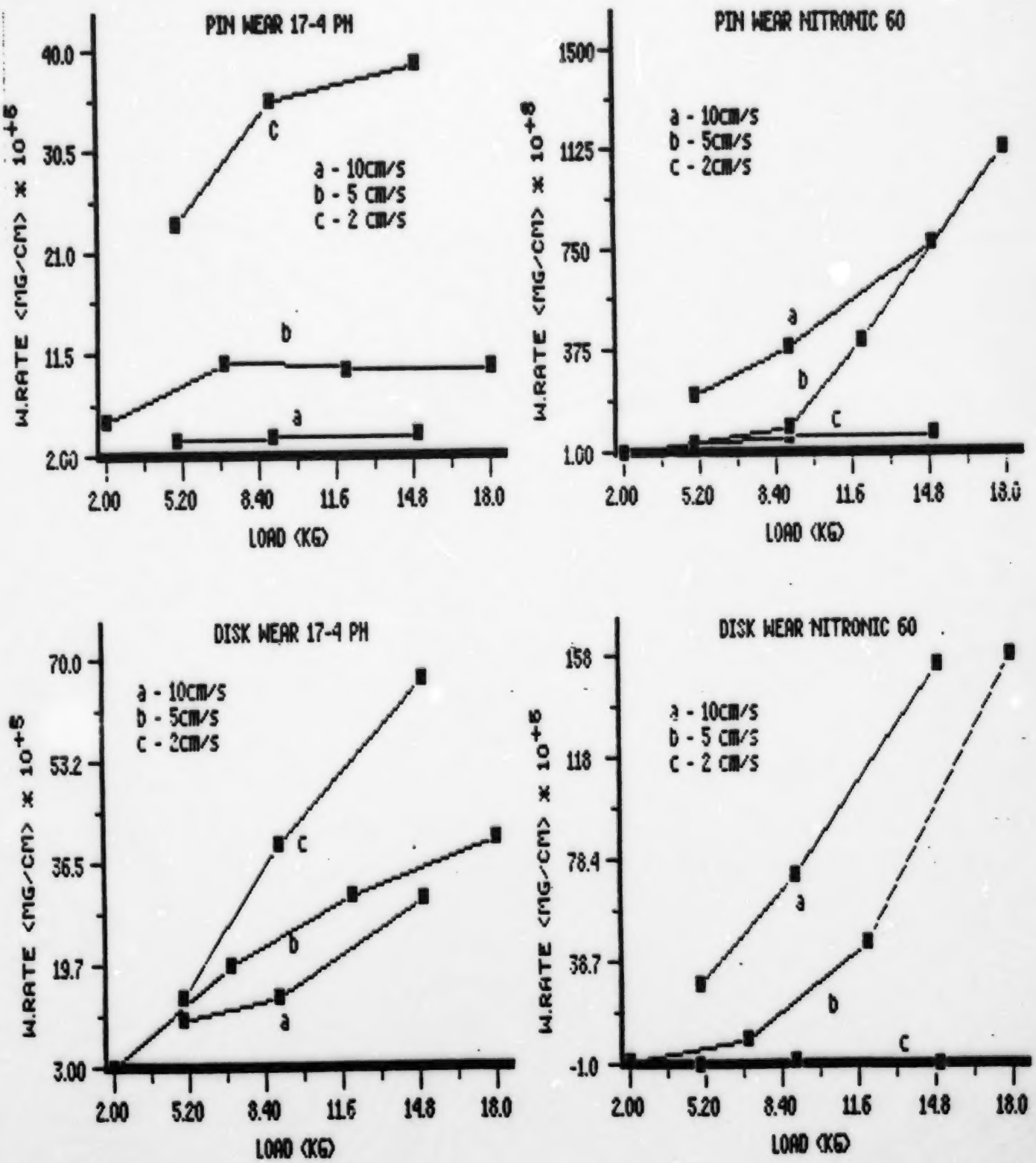


FIGURE 5

WEIGHT LOSS vs LOAD FOR NITRONIC 60
AND 17-4 PH TESTS